CORRECTING WIND SCATTEROMETERS FOR RAIN

Richard K. Moore, David Braaten, Vivek J. Kurisunkal, Bhaskar Natarajakumar, Govindan K. Narayanan, Jerome Arockiam

Radar Systems & Remote Sensing Lab
The University of Kansas
2335 Irving Hill Road Lawrence KS 66045, USA
rmoore@sunflower.com

INTRODUCTION

Scatterometers on spacecraft provide vector wind fields over the oceans. Those launched by the United States and Japan (Seasat, NSCAT, QuikSCAT, ADEOS-II) operate at Ku-band frequencies where backscatter from and attenuation through rain can corrupt the measurements. European systems (ERS-1/2, ASCAT) operating at C band are relatively unaffected by rain. For the Ku-band systems, one must somehow identify rain-corrupted data and either discard it or correct it. Here we concentrate on methods for scanning scatterometers like SeaWinds on QuikSCAT and ADEOS-II.

Rain in the scatterometer footprint corrupts the signal in three ways: Attenuation of the surface signal, backscatter from the rain itself that adds to the surface return, modification of the surface scatter at low wind speeds. This results in erroneous σ^0 readings that lead to faulty wind-vector solutions. Currently data believed to be corrupted by rain are "flagged" so that they are usually discarded. However, with sufficient information available from coincident radiometry, correction is possible as long as the rain rate is not too large.

RAIN FLAGS

Many papers describe methods for detecting rain corruption and flagging the corrupted data. The operational system for SeaWinds uses the MUDH algorithm[1]. This depends on use of 4 out of 5 parameters retrievable from the scatterometer data and available radiometry:
(1) Wind speed retrieved. If the values are large compared with those expected from models and adjacent areas, rain echoes probably are present. (2) Direction of the highest-rated ambiguity. Because of isotropy of rain echoes and rain modification of surface scatter, rain leads to retrieved directions normal to the flight track. (3) Difference (in opposite directions) in H and V polarization σ^0 values from those expected from the geophysical model function. (4) Small maximum-likelihood estimates caused by large variance of rain echoes. (5) High radiometric brightness temperatures from either Qrad (radiometry using the SeaWinds receiver), AMSR (on ADEOS-2), or nearly-coincident passes with radiometers on other satellites.
While all of these are indicators of the *presence* of rain, only the radiometer can indicate the rain rate. None of them can identify the fraction of the footprint that contains rain, and if this fraction is small the radiometer-derived rain rate can be seriously in error. Identification of the presence of rain and correction may involve both direct and indirect approaches. In the direct approach we have been using, one obtains estimates of the rain rate from a radiometer, the rain height from the rain rate, and solves the appropriate radar equation for the surface scattering coefficient.

Indirect methods for flagging usually use some combination of the first four approaches listed for MUDH. The idea of identifying unexpected MLE values has been used for some time[2]. Recently a modified version of the MLE that includes the rain rate was developed to estimate wind vectors and rain rates together [3]. It shows promise, as a means to get *effective* rain rate and wind vector without going through the direct correction process. Others have attempted to correlate rain rate with the scattering coefficient observed.[4]. Stiles and Yueh [5] report various correlations, and indicate the need for good radiometer data coincident with scatterometer data.

BASIS FOR CORRECTION

Correction depends on proper inversion of the equation for σ^0 in the presence of rain:

Received signal = attenuated surface signal + volume scatter from rain

$$\sigma^0_{meas} A = \sigma^0_{surf} A e^{-2 \int_{rainpath} k dr} + \eta H A \xi, \qquad (1)$$

where A is the effective illuminated surface area, k is the extinction coefficient in the rain, η is the volume scattering coefficient of the rain, σ^0_{surf} is the actual surface scattering coefficient that may be modified by the effects of rain drops striking the water, and ξ is a factor to correct for extinction of low-level rain echoes, given by $\xi = \frac{1}{SH}\int_0^{SH} e^{-2kR}\,dr$, where SH is the slant distance through the storm.

A is known from the satellite geometry and antenna beam width. k and η may be obtained from the rain rate, usually using suitable empirical relations. Radiometers such as AMSR on ADEOS-II produce rain-rate estimates. H must be found by some indirect method. Some authors use climatological data and others use some arbitrary value.

Thus, the corrected value for σ^0_{surf} is given by

$$\sigma^0_{surf} = \frac{\sigma^0_{meas} - \eta H \xi}{e^{-2\int_{rainpath} k dr}} \tag{2}$$

At Kansas we found that there is good correlation between storm height as reported by TRMM and rain rate, with different regressions applicable in northern and southern hemispheres and for stratiform and convective rain[[6, 7]]. Hence our approach uses these heights, which give results superior to climatological or arbitrary heights, thereby allowing improved corrections where possible and flagging if correction is impossible.

Correction by solving (1) is only possible if the second term is not much greater than the first, since the measurements of all quantities are noisy. This means that a threshold must be established between correctable cases and those in which a flag indicating unusable data must be set. σ^0_{surf} is a function of wind speed and direction; it is considerably larger in the upwind direction than at crosswind. Thus, one needs some rough estimate (say from nearby non-raining areas) to determine the wind vector, and then it can be used to decide whether to attempt correction or to flag the data as unusable.

We developed model thresholds from analysis of the regressions of height vs. rain rate using TRMM data from January, 1998 to January, 2002, and simulations of the corrections for which rms errors were calculated. The model thresholds based on the simulations are formulas that account for time of year, hemisphere and rain type. The thresholds are just a few mm/hr for wind speeds <about 7 m/s, particularly for directions approaching crosswind. With higher wind speeds and directions near upwind or downwind the thresholds are higher, but when rain is more than about 7 mm/hr, winds must be high for correction to be possible. This method can be applied to area-extensive storms (usually stratiform rain) for which radiometer data (such as that of ADEOS-2 (Midori-2)) are available along with the scatterometer data to allow height estimation.

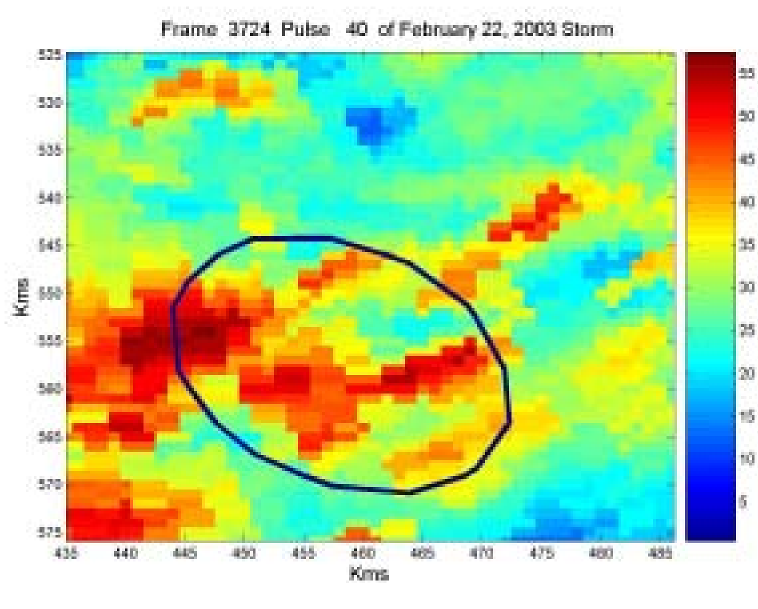


Fig. 1. Superimposing a SeaWinds footprint on a convective system, showing the variability of rain rate (shown as reflectivity) within the footprint

THE PROBLEM FOR CONVECTIVE SYSTEMS

In convective storm systems the individual intense cells are usually small relative to the scatterometer footprint. As a result both the brightness temperature due to the radiometer and the measured scattering coefficient are composites of the values from the different parts of their footprints. Figure 1 shows how variable a convective system can be within a SeaWinds footprint.

Correction is difficult in this situation. The brightness temperature T_B reported by the radiometer is an average for the footprint. Since the relation between rain rate and T_B is nonlinear, it is not the average rain rate. Even if it were the average rain rate, the rain backscatter per unit volume η

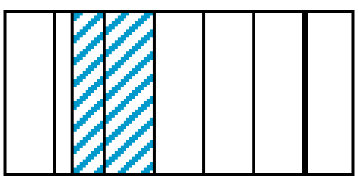
calculated from it would not be correct because of the nonlinearity of the relation between η and rain rate. Thus the values inserted into (2) would be wrong.

The SeaWinds instrument has a finer-resolution mode in which range and Doppler combine to produce data from "slices" that have the same transverse width as the normal mode (based on antenna beam width), but have improved resolution in the range direction. Nominally these slices have a range resolution of 7 km, although in some directions they may be smaller because of Doppler effects [Long, personal comm., 2005]. When there is heavy rain in a particular slice, and not in the others, its measured σ^0 will much larger than those of the other slices. This permits an estimate of the fractional rain cover in the footprint.

We may then use this fractional cover to improve the rain-rate estimate of the radiometer. Thus, if the fraction of the footprint covered is f, the rain rate for that slice can be estimated by using

$$R_{adj} = \frac{R_{reported}}{f}$$

since rain rate scales approximately linearly [8]. This rain rate can then be used to correct the scatterometer signal for the slice, and the total for all slices may then be appropriately modified. We simulated the performance of this technique and found that, under simulated conditions, it works well.



Fig, 2 Example of simulation footprint

An example of this simulation assumes a wind speed of 7 m/s and a zero degree wind direction with 25% storm coverage in the footprint, and rain rates up to 10 mm/hr. Fig. 2 shows the situation, with the cross-hatched area containing rain. For the example, the rain overlaps two slices, with less in one than in the other. We simulated the performance of the correction assuming both one and two slices to have rain, with the result shown in Figure 3. Clearly the errors are small. Further simulations show that the error is relatively insensitive to the quantization necessary because of the finite number of slices.

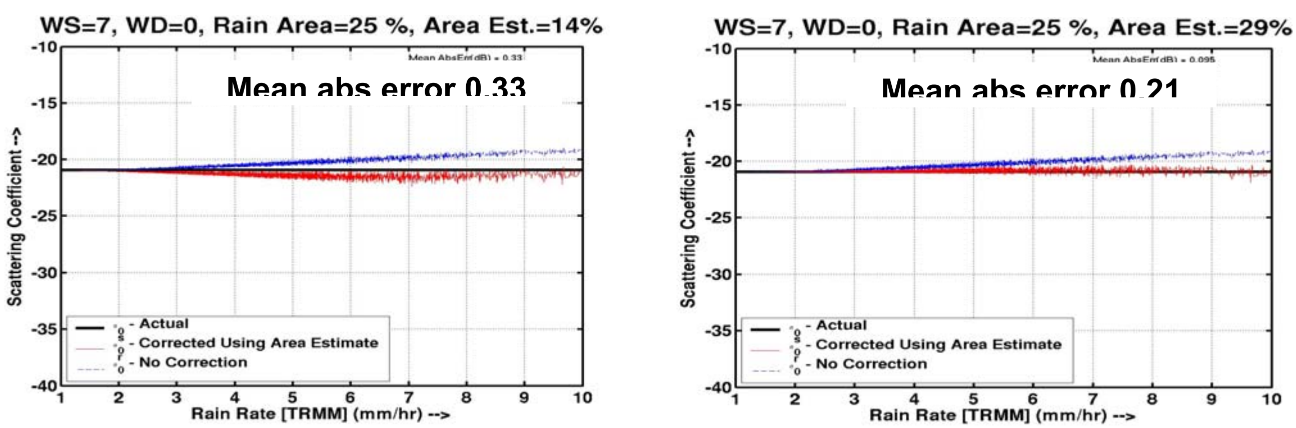


Fig. 3. Results of simulation

VERIFICATION USING NEXRAD DATA

Unfortunately, the real world is not as simple as our simulated example given above. In reality, slices in convective systems are rarely uniformly filled with constant rain, or even with rain at all. Fig. 4 shows an example of NEXRAD reflectivities for four slices from an actual SeaWinds pass over a convective storm. Slice footprints are approximately 5 km by 25 km, so the rain can be quite variable even in a single slice. This complicates the task of deciding which slices are rain-filled enough to modify the radiometer signal. Thus, establishing a proper criterion for separating "raining" and "non-raining" slices is difficult. We have not yet determined the exact value to use for this criterion.

Before developing such criteria, we are testing the performance of the σ^0 correction method using the relation between rain height and rain rate for individual slices by obtaining rain rates from coincident NEXRAD coverage. This is complicated because of the small width of the slices and the fact that the NEXRAD lowest beam strikes the storm at an

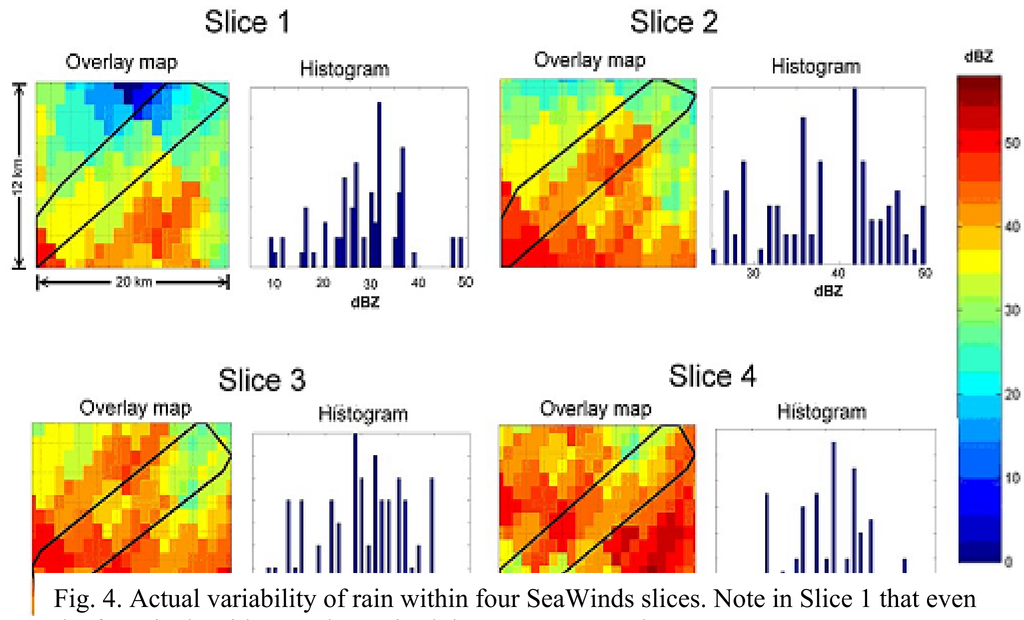


Fig. 4. Actual variability of rain within four SeaWinds slices. Note in Slice 1 that even the few pixels with > 45 dBZ raised the average to 37 dBZ

elevation determined by distance from the station. Attenuation is influenced by NEXRAD returns closer to the satellite and backscatter by NEXRAD returns farther from the satellite than the surface footprint. After compensating for this effect we find mean errors on the order of 1 dB and standard deviations of 2 to 3 dB for a small sample of data. We are expanding to a larger data set before drawing final conclusions. The results so far encourage us to believe that this method can work successfully.

CONCLUSIONS

Several methods permit flagging scatterometer data as rain-corrupted, with the MUDH algorithm used operationally, However, the large footprints of the scatterometer and radiometer tend to make these flags overly conservative. A correction method developed at the University of Kansas shows promise of allowing reasonable compensation for effects for modest rain rates so that fewer data need to be discarded even for convective systems.

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